

## HIGH INTENSITY $H^-$ CYCLOTRONS FOR RADIOISOTOPE PRODUCTION

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### ABSTRACT

*CYCLONE 30 is a 30 MeV,  $H^-$  cyclotron for radioisotope production, designed for extremely high extracted beam intensity (500  $\mu$ A) and low power consumption (less than 100 kW with a 15 kW extracted beam). The CYCLONE 30 prototype has now been operating for two years at LOUVAIN-LA-NEUVE and has achieved all design goals while demonstrating very high reliability. The major events in its development are reviewed. The data gathered so far give general basic trends for future designs : a 70 MeV, 2 mA machine design study is presented.*

### CYCLONE 30 DESIGN

Detailed design descriptions of CYCLONE 30 appear elsewhere [1], [2], [3] and are only summarized here (fig. 1).

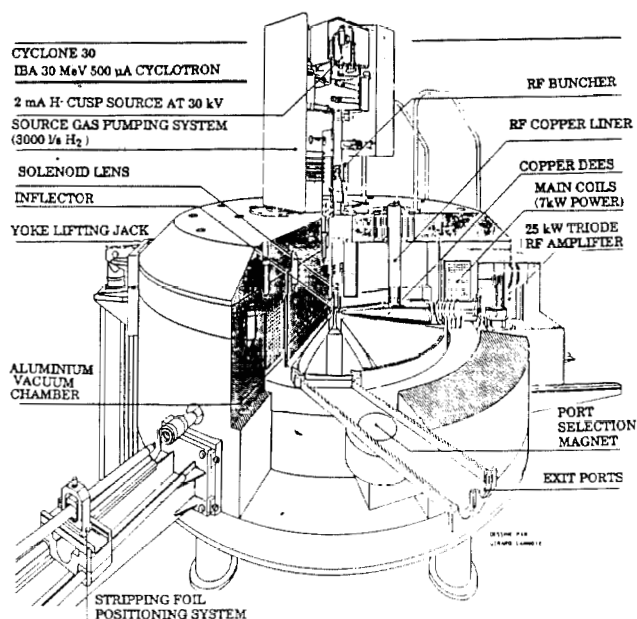


Figure 1:  
General layout of CYCLONE 30

CYCLONE 30 is a fixed field, fixed frequency, isochronous cyclotron designed to accelerate intense beams of  $H^-$  ions up to a maximum energy of 30 MeV.

The unusual magnet design combines the advantages of separated sector cyclotrons and solid pole cyclotrons. Energizing the cyclotron magnet requires as little as 7 kW. The magnetic field is adjusted during the manufacture by azimuthal shimming of the pole edges, providing a stable and highly isochronous field profile.

The rf system consists of two dees connected at the centre and operating on the 4th harmonic of the particle revolution frequency. The half-wavelength resonators are entirely located in the magnet valleys. The total power needed to obtain the nominal 50 kV dee voltage is only 5.5 kW per dee. The final stage rf amplifier, a grounded grid triode capable of delivering 26 kW, is attached to the cyclotron structure and coupled to the dees through a capacitor.

The negative hydrogen ions are produced by an external multicusp arc discharge ion source, biased at 29.5 kV. The axial injection system shown on fig. 2 includes two 15° bending magnets to select the appropriate beam species, a steering magnet, an electrostatic "EINZELL" lens, a beam stopper, a double gap rf buncher, a magnetic "GLASER" lens located in the cyclotron yoke and an electrostatic helicoidal inflector.

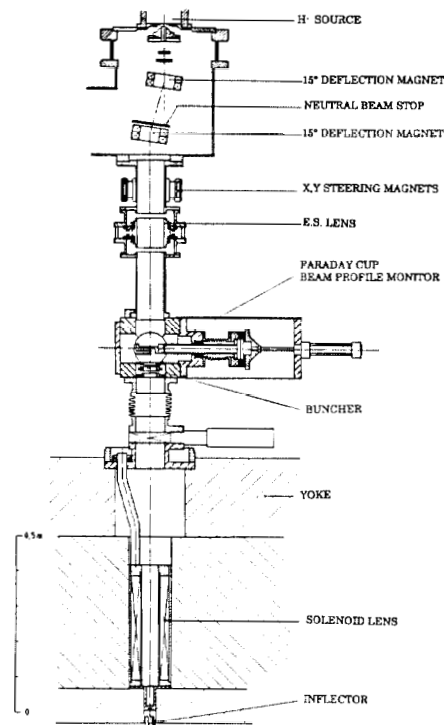


figure 2: The axial injection system

The  $H^-$  ions are extracted from the cyclotron by stripping through a thin carbon foil (40 mg/cm<sup>2</sup>). Continuously adjustable energy from 15 to 30 MeV is achieved by varying the radial position of the foil. Two beams may be extracted simultaneously at unrelated energies by means of two foils (one at each side).

Adequate pumping speed is provided by two oil diffusion pumps (1500 l/s per pump) and two cryogenic pumps (1500 l/s per pump). Typical operating pressure lies around  $5.10^{-7}$  mbar which keeps the rate of beam losses below 2%.

The control system consists of a Programmable Logic Controller running software developed in-house. Preset beams menus and function keys allow unskilled operators to run the machine.

#### DEVELOPMENT MILESTONES

- The assembly of the cyclotron was completed in December 1986,
- 24th Dec. 86 : The first  $H^-$  beam was accelerated to the full energy of 31.5 MeV.
  - Jan. 87 : The installation of the extraction system was completed.
  - Feb. 87 : The first beam was extracted with 100 % extraction efficiency and optical properties were in agreement with calculations.
  - May 87 : The extracted current reached 170  $\mu A$ . However, lack of shielding precluded the continuation of high current tests at the initial assembly location.
  - July - Aug. 87 : The cyclotron was installed in its final vault with sufficient shielding for higher intensity beams.
  - Oct. 87 : The extracted beam current reached 285  $\mu A$ . At this intensity, pressure fluctuations increased beam neutralisation. In order to avoid these beam losses, the pumping speed on the cyclotron was increased by adding two cryopumps.
  - Dec. 87 : First test of the stripping foil lifetime : 200 hours of continuous operation with an extracted current of 250  $\mu A$  required only two foils.
  - Jan. - June 88 : Improvements in the ion source extraction brought the maximum intensity to 400  $\mu A$  in routine operation.
  - July 88 : The extracted beam current reached 530  $\mu A$ . But, in some circumstances, the beam load on the rf system exhibited a negative dynamic resistance causing amplitude oscillations to develop. This problem was cured by improving the rf amplitude regulation loop.  
Due to the AC power supply of the ion source filament, the injected beam was modulated at 100 Hz with sharp peaks that caused the rf protection system to trip. Installation of a DC filament power supply solved this problem.
  - Aug. 88 : Uninterrupted test for 24 hours with 450  $\mu A$  at 30 MeV.
  - Nov. 88 : Differential pumping on the source by adding a turbomolecular pump increased the axial injection efficiency (with buncher) from 20 % to 29 % for an injected beam of 2 mA.
  - Dec. 88 : The extracted current repeatedly reached 580  $\mu A$ .
  - Feb. 89 : A method to measure the losses of  $H^-$  beam was developed and tested. The rate of beam losses may now be monitored, irrespective of pressure measurement and may be used as a warning signal to prevent unnecessary activation of the inner parts of the cyclotron.

The pump-down time was shortened with two U.V. light bulbs installed in the vacuum chamber. Measurements showed a significant gain of time (25 minutes) before resuming operation after a vacuum system shutdown.

#### CURRENT STATUS

Those developments were made in alternance with routine production of P.E.T radioisotopes. CYCLONE 30 also runs at high intensity ( $\sim 300 \mu A$ ) to irradiate solid targets for more than 400 hours per month. It also contributes to a nuclear physics research project (Radioactive Ion Beams) in which large amounts of  $^{13}N$  (200 Ci at equilibrium) are produced by bombarding a  $^{13}C$  enriched target.

In conclusion, the operating experience with the prototype of CYCLONE 30 shows that :

- Very high extracted currents are possible (580  $\mu A$  with 2 mA ion source current).
- Low power consumption and high electrical energy conversion efficiencies are possible (CYCLONE 30 uses 58 kW plus twice the extracted beam power).
- Fully automatic unattended operation can be achieved.
- Very low activation can be maintained on a high intensity cyclotron (radioactivity level always below 30 mRH $^{-1}$  after a few hours everywhere inside the cyclotron).

During these 2 years of beam development and operation, the overall reliability of the cyclotron has been excellent.

#### CYCLONE 70 : A 70 MeV - 2 mA ACCELERATOR

The results obtained with the CYCLONE 30 design stimulate extrapolation for a higher energy cyclotron. Here are some aspects of the feasibility study which has recently been carried out.

#### MAGNET

CYCLONE 70 has the same design as CYCLONE 30. Obviously, electromagnetic stripping comes first to mind when trying to increase the energy of a negative ion accelerator. Calculations show that beam losses may be kept below 2 % with a maximum magnetic field of 1.65 Tesla which compares well with the maximum induction in CYCLONE 30 (1.7 T).

With this magnetic field, the hill and valley angles have been calculated. The hill angle is 49.5° at the centre of the cyclotron and 54° at the extraction radius. With a hill angle of 54°, the pole radius is 1.40 m.

Vertical focusing calculations show that sector spiralization is not required.

Power consumption has been estimated for various yoke dimensions.

Two yoke dimensions corresponding to a minimum weight and to a minimum power consumption were finalised. The first yoke weighs 179 tons and the power consumption of the coils is 18 kW. The second yoke has a weight of 208 tons with a coil power consumption of only 5.5 kW. The choice must be made between a high investment cost followed by low operating costs and vice versa.

#### RADIOFREQUENCY

The rf system operates at 57.27 MHz to accelerate the particles on the 4th harmonic mode.

The two dees have an average angle of  $40^\circ$  which yields a fair energy gain per gap crossing (90% of peak voltage). With a dee voltage of 75 kV, the dissipated power per cavity is 12.5 kW. The acceleration power is 35 kW (500  $\mu$ A at 70 MeV). A rf system efficiency around 50 % gives a total power consumption of 120 kW. The dee voltage of 75 kV enables particles to be accelerated up to 70 MeV with only 259 turns. This feature sets the limit for magnetic field stability to only  $1 \cdot 10^{-4}$ .

### INJECTION

With the same central region and injection system design as CYCLONE 30 an extracted current of 500  $\mu$ A may easily be reached. Preliminary calculations of space charge effects show that an ion source delivering 10 mA of  $H^-$  and biased at 120kV would enable CYCLONE 70 to accelerate 2 mA of beam current, with a suitable rf amplifier (140 kW). Such bias voltages and source currents are completely within the state of the art.

### EXTRACTION

An extraction system similar to that of CYCLONE 30, with two opposite foil holders and extended radial reach allows two beams to be extracted simultaneously at unrelated energies between 15 and 70 MeV.

CYCLONE 30 and CYCLONE 70 main characteristics are given in table 1.

### CONCLUSIONS

The high level of confidence gained in the design of CYCLONE 30 during two years of operating experience with the prototype leads to an almost straightforward and uncritical design for a 70 MeV cyclotron. A further increase in intensity is also well within the reach of the current state of the art.

### REFERENCES:

- [1] Y. Jongen and G. Ryckewaert : "Preliminary Design for 30 MeV-500  $\mu$ A  $H^-$  Cyclotron", Particle accelerator Conf., Vancouver, B.C., I.E.E.E. Trans. science, Vol. NS-32, N<sup>o</sup> 5, pp. 2703-2705, October 1985.
- [2] Y. Jongen, J.L. Bol, A. Chevalier, M. Lacroix and G. Ryckewaert : "Construction of the Louvain-La-Neuve 30 MeV-500  $\mu$ A  $H^-$  Cyclotron", 11th Int. Conf. on Cyclotrons and their Applications, Tokyo, October 13-17 1986.
- [3] Y. Jongen, G. Ryckewaert and S. Zarembo : "Beam dynamics Aspect of high Intensity Isotope Production Cyclotron", 11th Int. Conf. on Cyclotrons and their Applications, Tokyo, October 13-17 1986.

Table 1 : Main parameters

	CYCLONE 30	CYCLONE 70
<b>Beam</b>		
Type of ions		
-extracted :	$H^+$	$H^+$
-accelerated :	$H^-$	$H^-$
Variable energy <MeV> :	15-32	15-70
Maximum intensity < $\mu$ A> :	500	500
Max. beam lines :	4	10
Number of beams extracted simultaneously :	2	2
Normalized emittance <mm mrad>		
-horizontal :	< $10\pi$	< $10\pi$
-vertical :	< $5\pi$	< $5\pi$
<b>Magnetic structure</b>		
Number of sectors :	4	4
Sector angle (radially varying) <degree> :	54-58	49-54
Magnetic induction <T>		
Hill :	1.7	1.6
Valley :	0.12	0.12
Coil power consumption <kW> :	7.1	18
Mass <tons>		
Iron :	45	179
Copper :	4	13.4
<b>R.F system</b>		
Number of dees (connected at the centre) :	2	2
Effective dee angle <degree> :	30	40
Harmonic mode :	4	4
Frequency (fixed) <MHz> :	6.5	52.27
Nominal dee voltage <kV> :	50	75
Dissipated power		
-per cavity <kW>:	5	12.5
-beam acceleration <kW> :	15	35
<b>Injection</b>		
Type of source (external) :	cuspl	cuspl
Filament power <kW> :	0.5	0.5
Arc power <kW> :	2	5
H2 flow rate <scm> :	5-10	10-20
Source bias <kV> :	30	30
Injected $H^-$ current <mA> :	2	3